NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3599

TURBULENT-HEAT-TRANSFER MEASUREMENTS AT A MACH NUMBER OF 0.87

By Maurice J. Brevoort and Bernard Rashis

Langley Aeronautical Laboratory
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SUMMARY

Turbulent-heat-transfer measurements were obtained through the use of an axially symmetric annular nozzle which consists of an inner shaped center body and an outer cylindrical sleeve. Measurements taken along the outer sleeve gave essentially flat-plate results that are free from wall interference and corner effects for a Mach number of 0.87 and for a Reynolds number range from 9.88×10^6 to 2.09×10^8. The heat-transfer coefficients are slightly higher than theoretical results for a Mach number of 1.0 and for a ratio of inner surface temperature to free-stream temperature of 1.0, and they agree with theoretical results for incompressible flow. The temperature-recovery factors range from 0.899 at a Reynolds number of 9.88×10^6 to 0.876 at a Reynolds number of 2.09×10^8.

INTRODUCTION

The design of high-speed aircraft requires engineering information about heat-transfer coefficients and temperature-recovery factors for high speeds that extend over a wide range of Reynolds number. In references 1, 2, and 3, local turbulent-heat-transfer measurements were presented for Mach numbers of 3.03, 2.06, and 1.62, respectively.

The purpose of this investigation is to extend the work of references 1, 2, and 3 to a Mach number of 0.87 with the same type of data and method of reducing the data. The range of Reynolds number for which measurements were obtained was from 9.88×10^6 to 2.09×10^8. The ratio of the inner surface temperature to free-stream temperature varied from 1.18 to 1.15.

SYMBOLS

c	specific heat of sleeve material, Btu/lb-°R
c_p	specific heat of air at constant pressure, Btu/lb-°R
g	acceleration due to gravity, ft/sec^2
h	heat-transfer coefficient, Btu/ft^2-sec-°R
k	heat conductivity, Btu/ft-sec-°R
M	Mach number
Nu	Nusselt number, hx/k
Pr	Prandtl number, $\mu c_p g/k$
R	Reynolds number, $\rho V x/\mu$
St	Stanton number, $\frac{Nu}{R\ Pr} \equiv \frac{h}{\rho V c_p g}$
T_{av}	average wall temperature, °R
T_e	effective stream air temperature at wall, some temperature which gives a thermal potential which is independent of heat-transfer coefficient, °F
T_t	stagnation temperature, °R
T_w	inner surface temperature of nozzle sleeve, °R
T_∞	free-stream temperature, °R
t	time, sec
V	free-stream velocity, ft/sec
w	specific weight of sleeve material, lb/sq ft
x	longitudinal distance along sleeve, ft (unless indicated otherwise)

η_r recovery factor, $\frac{T_e - T_\infty}{T_t - T_\infty}$

μ dynamic viscosity coefficient, lb-sec/sq ft

ρ free-stream density of air, slugs/cu ft

APPARATUS AND METHOD

The apparatus consisted of an axially symmetric nozzle which was directly connected to the settling chamber of one of the cold-air blowdown jets of the Langley gas dynamics laboratory. The nozzle had a shaped wooden center body and an outer sleeve constructed from an 8-inch-diameter, extra heavy, seamless, carbon-steel pipe. The outer sleeve was surface machined inside and outside to a wall thickness of 0.388 inch.

A detailed drawing of the apparatus is shown in figure 1, which gives the location of the thermocouples and static-pressure orifices. Details of the apparatus and measuring equipment are given in references 1 and 2.

The dimensions of the inner plug, corrected for boundary-layer growth, are shown in figure 1. The Mach number was 0.87 over the entire test region.

For this investigation, test runs were made for settling-chamber pressures of 15, 54, 101, and 202 lb/sq in. gage. Excluding the first 20 seconds, the pressures were maintained constant for each test run. The stagnation temperature started at essentially room temperature and decreased as the piping was cooled, as illustrated in figure 2 where stagnation temperature is plotted against time for a settling-chamber pressure of 54 lb/sq in. gage. The wall temperature started approximately 10° R to 15° R above the stagnation temperature and tended to approach the equilibrium temperature which was approximately 6° R below stagnation temperature. This variation is shown in figure 3 where wall temperature at station 27 is plotted against time for a settling-chamber pressure of 54 lb/sq in. gage.

In figure 4, the values of wall temperature are plotted against longitudinal distance along the cylinder for various times during the test run. These values were used to determine the rate of change of the longitudinal conduction $k\frac{d^2T_{av}}{dx^2}$ along the cylinder. Results were taken only for the length of the cylinder for which $k\frac{d^2T_{av}}{dx^2} = 0$.

REDUCTION OF DATA

The equations used in reducing the data are

$$\eta_r = \frac{T_e - T_\infty}{T_t - T_\infty} \tag{1}$$

$$h = wc\frac{dT_{av}/dt}{T_w - T_e} \tag{2}$$

$$St = \frac{h}{\rho V c_p g} \tag{3}$$

and

$$Nu = St\ R\ Pr \tag{4}$$

The method consists of selecting a recovery factor and then obtaining T_e from equation (1). For each recovery factor that is selected, the corresponding quantity $T_w - T_e$ is determined and then plotted against the quantity $wc\frac{dT_{av}}{dt}$ (the heat input). The curve connecting these points is a straight line (eq. (2)). The true values of T_e and η_r are obtained when the line goes through zero. The slope of this line is the value of h. Figure 5 shows the values used in determining η_r and h at station 27 for a settling-chamber pressure of 54 lb/sq in. gage.

The Stanton number is calculated from equation (3); and the Nusselt number, from equation (4). The values of Prandtl number (0.71) and viscosity of air were taken from reference 4 and were based upon T_w. The value of T_w used was that value measured 80 seconds after starting. The values of specific heat and specific weight of the sleeve material were also taken from reference 4.

RESULTS AND DISCUSSION

Over the test range (see fig. 4), the wall temperatures are constant along x. In equation (2), w and c are constant, and dT_{av}/dt is constant because T_w is constant. Therefore, if there is to be a variation of h with Reynolds number or x, T_e must vary with x. The value of T_e obtained for the test at a settling-chamber pressure of 54 lb/sq in. gage, evaluated 80 seconds after starting, actually decreases about 0.6°.

Figure 6 shows the variation of local Nusselt number with local Reynolds number. The value of x used in evaluating these numbers was considered to be zero at the upstream end of the sleeve (the beginning of the turbulent boundary layer). The results indicate that this is the correct location of the $x = 0$ location.

The Nusselt numbers were found to vary from 8,118 to 123,323 for the Reynolds number range from 9.88×10^6 to 2.09×10^8. For comparison, the curves based on the Van Driest analysis (ref. 5) are shown for $M = 1.0$ and $M = 0$ with $T_w/T_\infty = 1.0$. The average value of T_w/T_∞ for the test results was 1.15.

The data were computed by using free-stream temperature to determine the density and velocity. The wall temperature was used to determine the viscosity and Prandtl number. The data are slightly above the $M = 1.0$ curve and are in good agreement with the incompressible curve.

Figure 7 shows the variation of local temperature-recovery factor with local Reynolds number. The variation is from 0.899 at 9.88×10^6 to 0.876 at 2.09×10^8. Also included for comparison are the curves for the recovery factor equal to $Pr^{1/3}$ and $Pr^{1/2}$. The wall temperature was used to determine the Prandtl number.

CONCLUDING REMARKS

Turbulent-heat-transfer measurements that gave essentially flat-plate results were obtained for a Mach number of 0.87 and for a Reynolds number range from 9.88×10^6 to 2.09×10^8. The Nusselt numbers agreed with incompressible theory and are slightly higher than theoretical results for a Mach number of 1.0. The temperature-recovery factors decreased from

0.899 at a Reynolds number of 9.88×10^6 to 0.876 at a Reynolds number of 2.09×10^8.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 20, 1955.

REFERENCES

1. Brevoort, Maurice J., and Rashis, Bernard: Turbulent-Heat-Transfer Measurements at a Mach Number of 3.03. NACA TN 3303, 1954.

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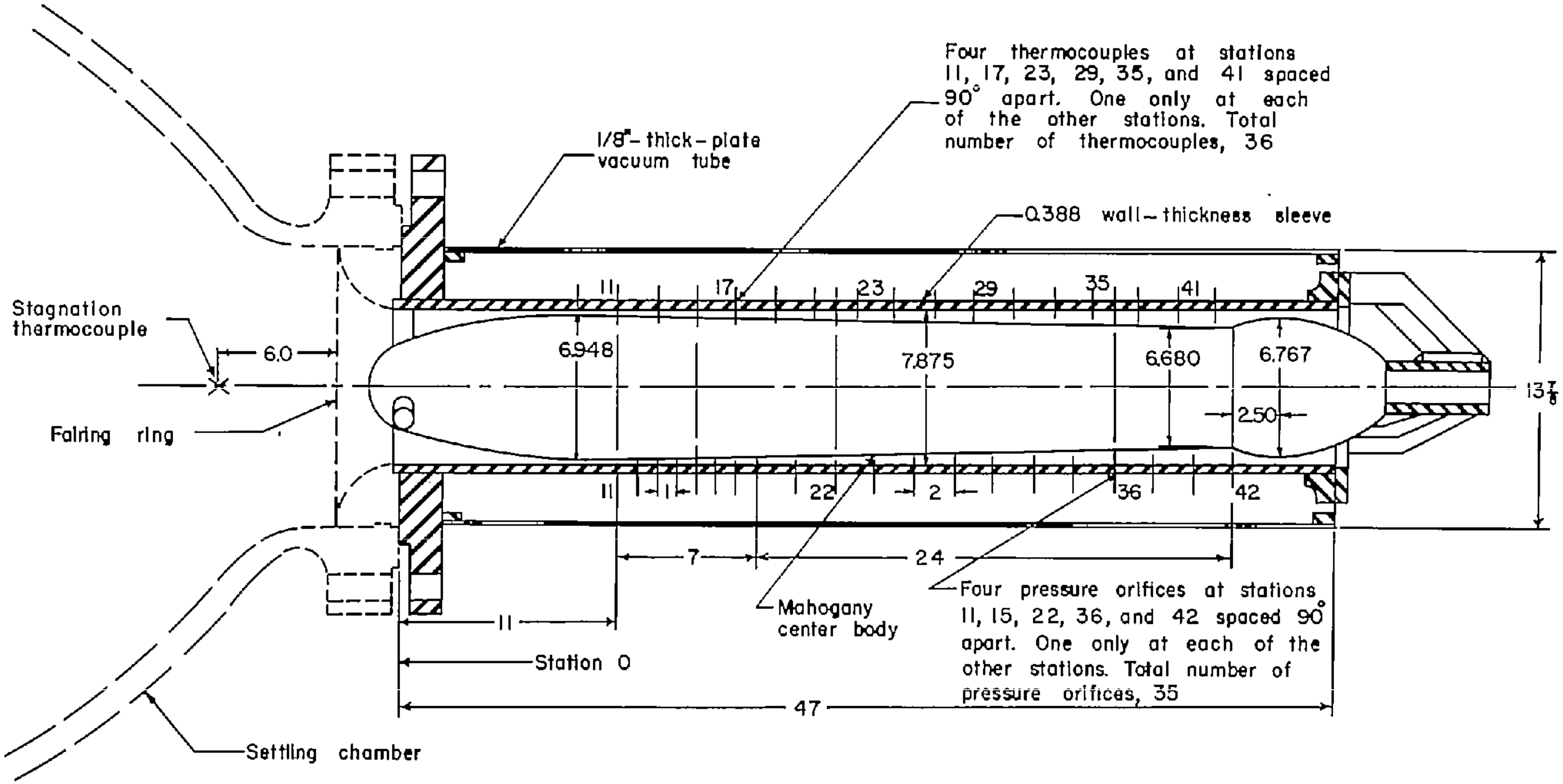

Figure 1.- Test setup. All dimensions are in inches.

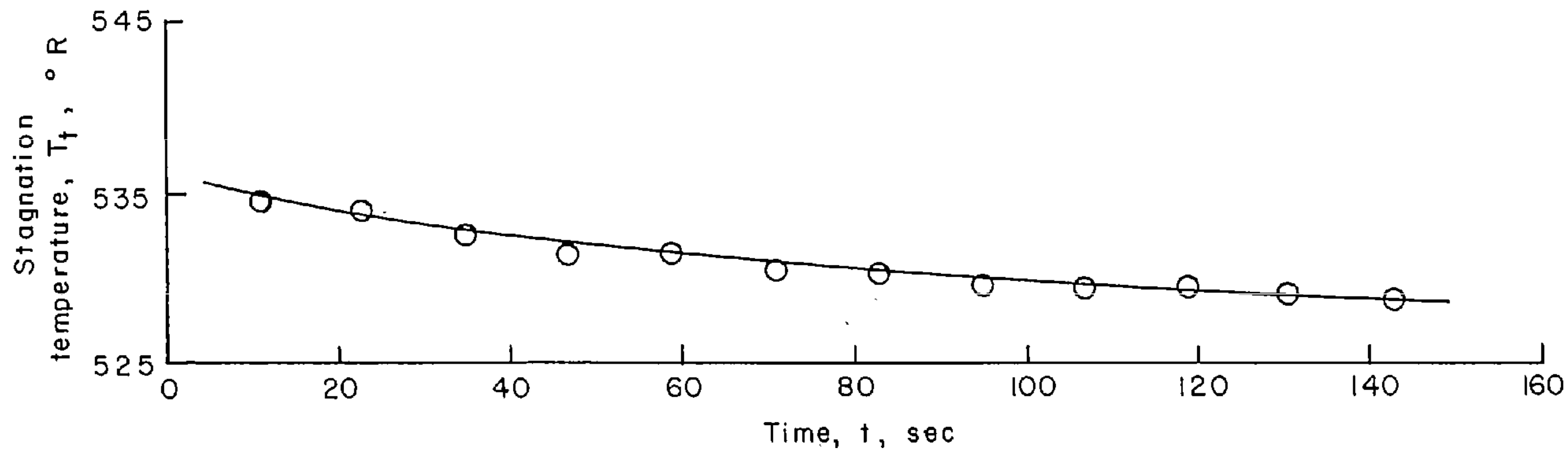

Figure 2.- Variation of stagnation temperature with time for settling-chamber pressure of 54 lb/sq in. gage.

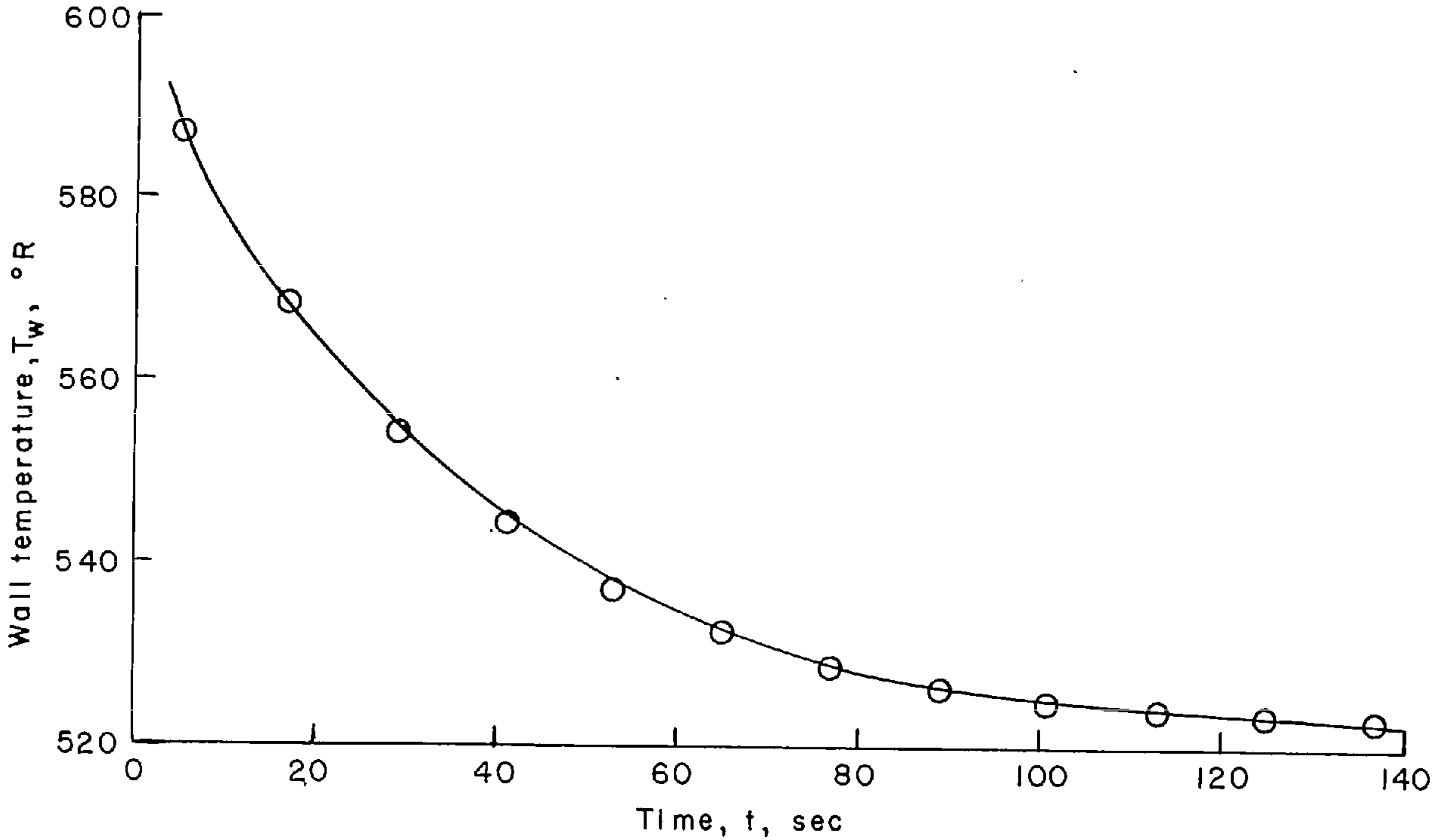

Figure 3.- Variation of wall temperature with time at station 27 for settling-chamber pressure of 54 lb/sq in. gage.

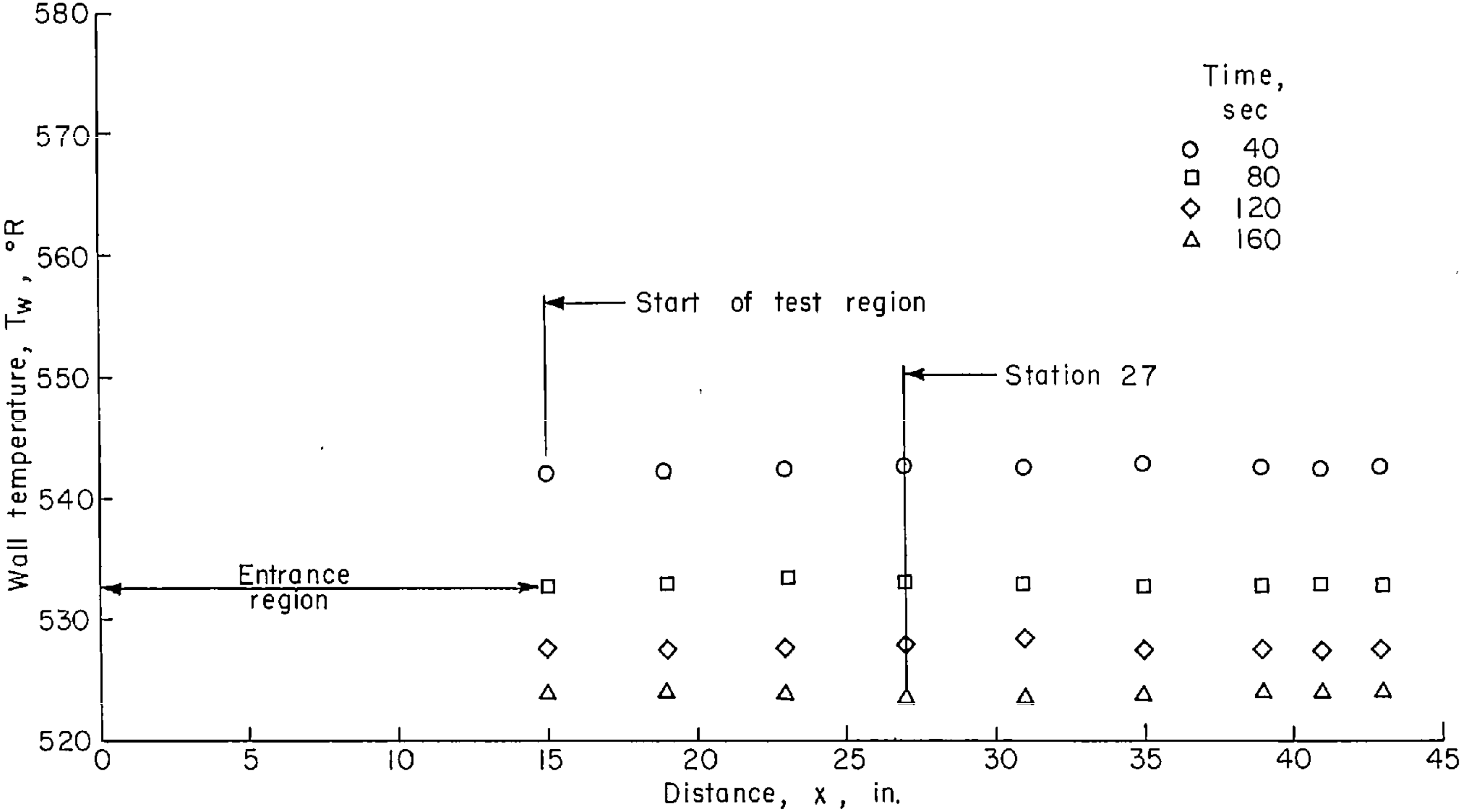

Figure 4.- Variation of wall temperature with longitudinal distance for settling-chamber pressure of 54 lb/sq in. gage.

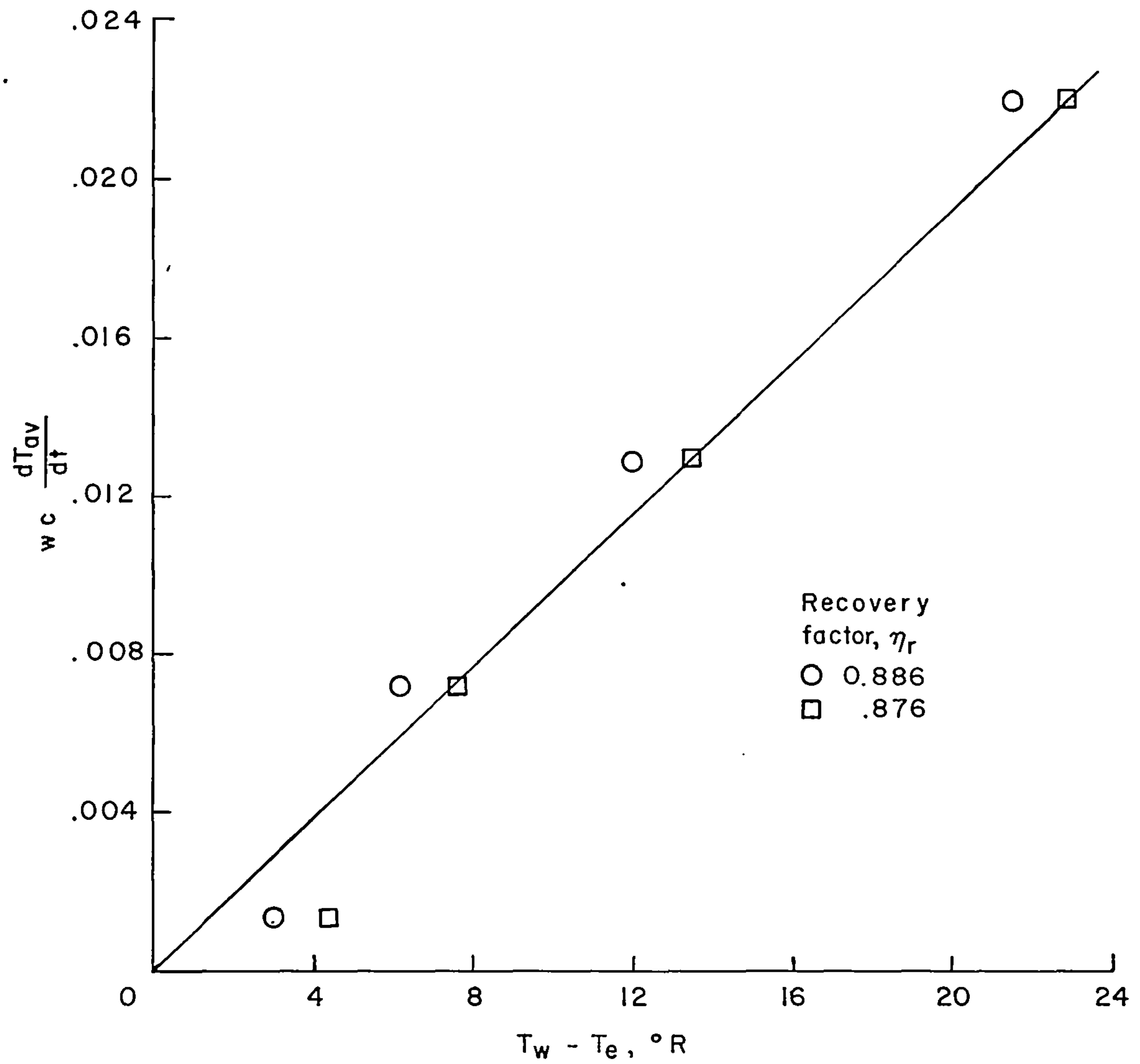

Figure 5.- Heat input as a function of recovery factor and $T_w - T_e$ at station 27 for a settling-chamber pressure of 54 lb/sq in. gage.

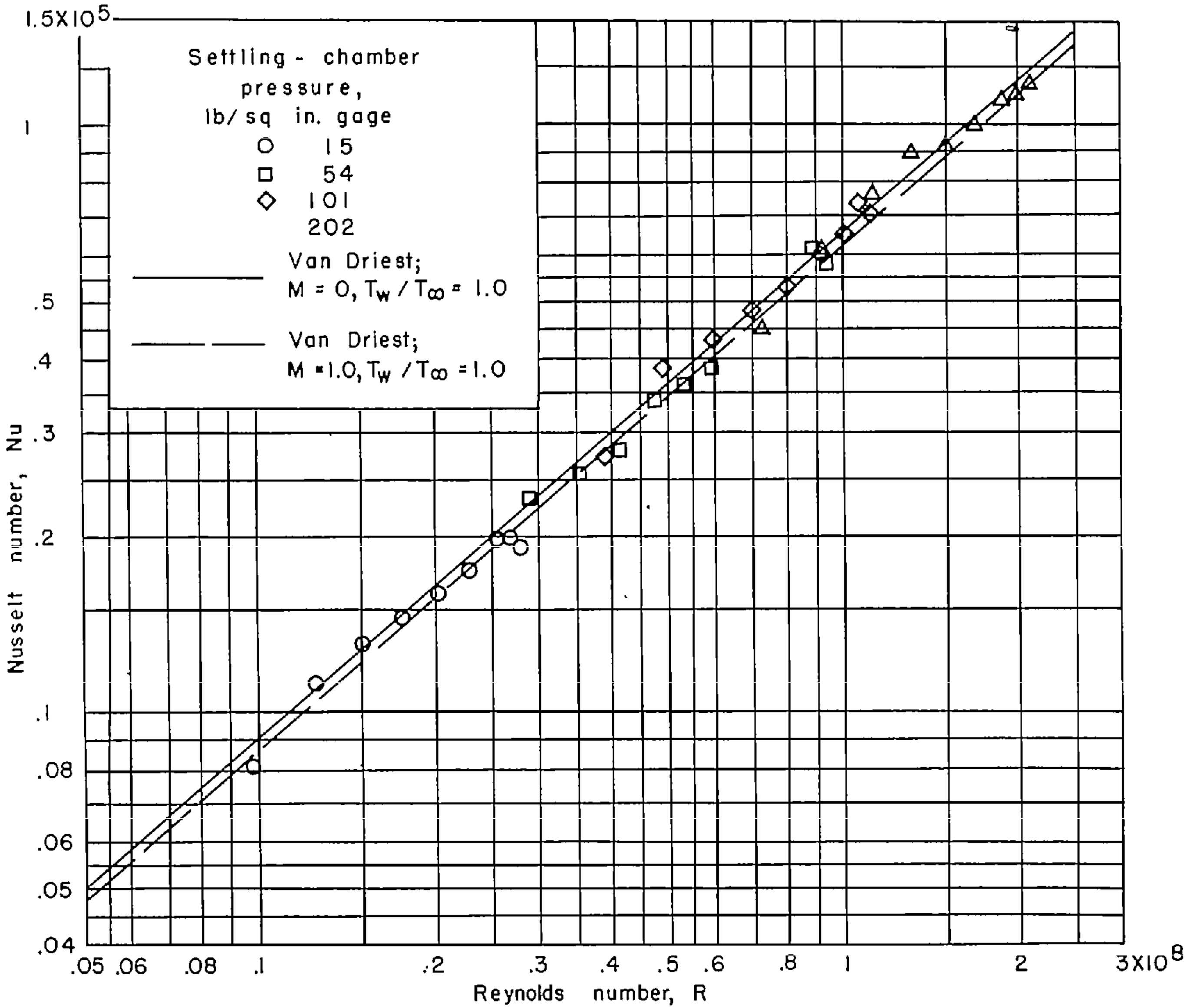

Figure 6.- Variation of local Nusselt number with local Reynolds number.

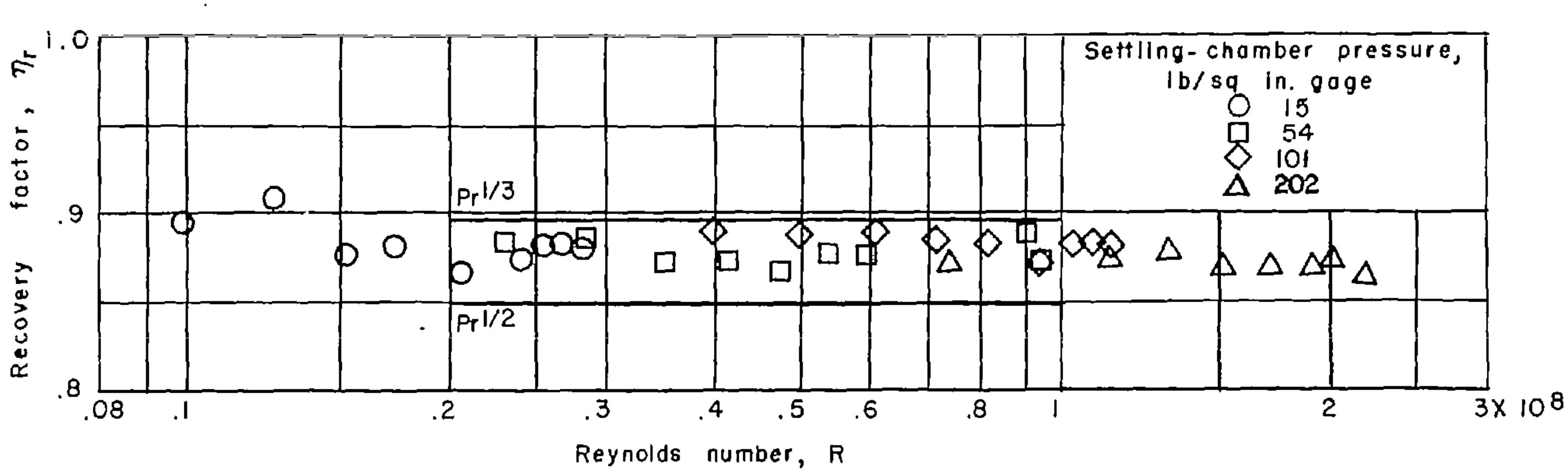

Figure 7.- Variation of local recovery factor with local Reynolds number.